Proceedings of the
Institute of Acoustics

Volume 15 Pt 2 1993

Acoustic Classification and Mapping of the Seabed

an Underwater Acoustics
Group Conference held at
the University of Bath,
14th – 16th April 1993
Co-sponsored by
Defence Research Agency.

REPORT DOCUMENTATION PAGE

Form Approved
OBM No 0704-0188

1. Agency Use Only *(Leave blank).*

2. Report Date.
April 1993

3. Report Type and Dates Covered.
Final - Proceedings

4. Title and Subtitle.
Development of a High Resolution Acoustic Seafloor Classification Survey System

5. Funding Numbers.
Program Element No 0603785N
Project No
Task No
Accession No DN252052
Work Unit No 571521503

6. Author(s).
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7. Performing Organization Name(s) and Address(es).
Naval Research Laboratory
Marine Geosciences Divison
Stennis Space Center, MS 39529-5004

8. Performing Organization Report Number.
NRL/PP/7431--92-0004

9. Sponsoring/Monitoring Agency Name(s) and Address(es).
Office of Naval Research Detachment
Stennis Space Center, MS 39529-5004

10. Sponsoring/Monitoring Agency Report Number.
NRL/PP/7431--92-0004

11. Supplementary Notes.
Published in Proceedings of the Institute of Acoustics.

12a. Distribution/Availability Statement.
Approved for public release; distribution is unlimited.

12b. Distribution Code.

13. Abstract *(Maximum 200 words).*

A need exists in both the civilian and military communities for an automated seafloor classification system that can remotely and accurately estimate and map sediment properties for a number of seafloor engineering applications and for input to acoustic propagation prediction models. Over the past several years the Naval Research Laboratory (NRL) has been developing a normal incidence, narrow beamwidth, high resolution seismic system that has the capability to accurately predict, in near real-time, acoustic impedance, sediment type and a number of selected geotechnical properties of the upper several meters of the seafloor while in an underway survey mode, Lambert (1). The system is designated the Acoustic Seafloor Classification System (ASCS) and is technology based on the Echostrength Measuring System (EMS) developed in the early 1980's by Honeywell ELAC of Kiel, Germany. A detailed description of this system can be found in Lambert and Fielder (2).

14. Subject Terms.
Acoustic, sediment, classification, seafloor

15. Number of Pages.
8

16. Price Code.

17. Security Classification of Report.	**18. Security Classification of This Page.**	**19. Security Classification of Abstract.**	**20. Limitation of Abstract.**
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

DEVELOPMENT OF A HIGH RESOLUTION ACOUSTIC SEAFLOOR CLASSIFICATION SURVEY SYSTEM

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1. INTRODUCTION

A need exists in both the civilian and military communities for an automated seafloor classification system that can remotely and accurately estimate and map sediment properties for a number of seafloor engineering applications and for input to acoustic propagation prediction models. Over the past several years, the Naval Research Laboratory (NRL) has been developing a normal incidence, narrow beamwidth, high resolution seismic system that has the capability to accurately predict, in near real-time, acoustic impedance, sediment type and a number of selected geotechnical properties of the upper several meters of the seafloor while in an underway survey mode, Lambert (1). This system is designated the Acoustic Seafloor Classification System (ASCS) and is technology based on the Echostrength Measuring System (EMS) developed in the early 1980's by Honeywell ELAC of Kiel, Germany. A detailed description of this system can be found in Lambert and Fiedler (2).

Our current thrust toward the development of a system capable of rapidly and accurately classifying the seafloor requires a thorough understanding of the interaction between environmental, geotechnical, and acoustic parameters. It is surprising how little work has been done over the years in relation to these problems, particularly for shallow water areas. Clearly a great deal of work is required in order to gain an understanding of these environmental effects in relation to remote seafloor classification, which must include both basic and applied research. It is probable that even with a much greater understanding of these relationships, that minimal ground truth sediment core data will still be required in order to "tune" the acoustic predictive data to the particular environment where a survey is run. This is not surprising, when we consider the highly variable sediment types, structures, compositions, and consistencies that exist, particularly in shallow water areas.

The ASCS under development by NRL is being designed with a dual function in mind: (1) to function as a flexible research data acquisition platform for the collection of experimental data, and (2) to function as the prototype which will become the system capable of accurately classifying the seafloor in routine survey operations. The exact specifications of this final system are currently being defined. Indeed, a prime design driver for the NRL system currently under development is to produce the experimental databases required to specify the operational parameters of the final system. Basic questions which are being addressed are:

1. Is it possible to accurately characterize the seafloor under all environmental conditions?
2. What is the confidence level?
3. What are the fundamental limitations?

A key aspect to obtaining the required data is a flexible acquisition system. As research toward [illegible] understanding of the required seafloor classification methodology proceeds, a system is needed which is [illegible] rapid reconfiguration in order to acquire unique data sets. Such a system would not need to be redesigned [illegible] extensively modified for each experiment. We are currently developing this system through a [illegible] interrelated basic and applied research projects. We have had to anticipate which capabilities [illegible] important for the ASCS research and will lead to the required hardware/software systems. Key requirements are expected to be (1) multiple frequency operation, (2) a calibrated system, and (3) an extremely accurate data acquisition system capable of minimum distortion of the received bottom return.

2. BACKGROUND

The original EMS consisted of a narrow beam (12°) 15 kHz transducer, a high resolution analog paper recorder (LAZ 72), and an 8085 microprocessor-controlled signal processor (EMG2) that quantitatively measured the return echo strength in ten adjustable time windows that corresponded to depth intervals in the sediment. Either the first five or the last five of these echo strength lines are plotted on the seismogram (Fig. 1). The relative spread of the lines away from a baseline indicates the strength of the echo return in each of the time windows. Wide separation between the lines denotes a strong acoustic return and a highly reflective sediment such as sand. Narrow separation between the lines indicates low reflectivity or soft muddy sediments. An experienced operator could subjectively predict the type of sediment below the transducer fairly well using this method, Howard and others (3). In order to quantify the acoustic return, NRL contracted Honeywell ELAC in the mid 1980's to develop a near real time software program that computes an acoustic impedance profile of the sediment for each ping. From the acoustic impedance profile, several empirical relationships, primarily developed by Hamilton (4) and Hamilton and Bachman (5), could be used to predict a number of sediment geotechnical properties in near real time while in a survey mode. This software program was developed around a DEC Pro 350 color computer which was the state-of-the-art micro-computer at the time. Although this computer served its purpose well and provided the means to evaluate and verify the concept of remote acoustic seafloor classification, it's signal processing capability was severely limited, particularly when compared to todays micro-computer data processing and storage capabilities.

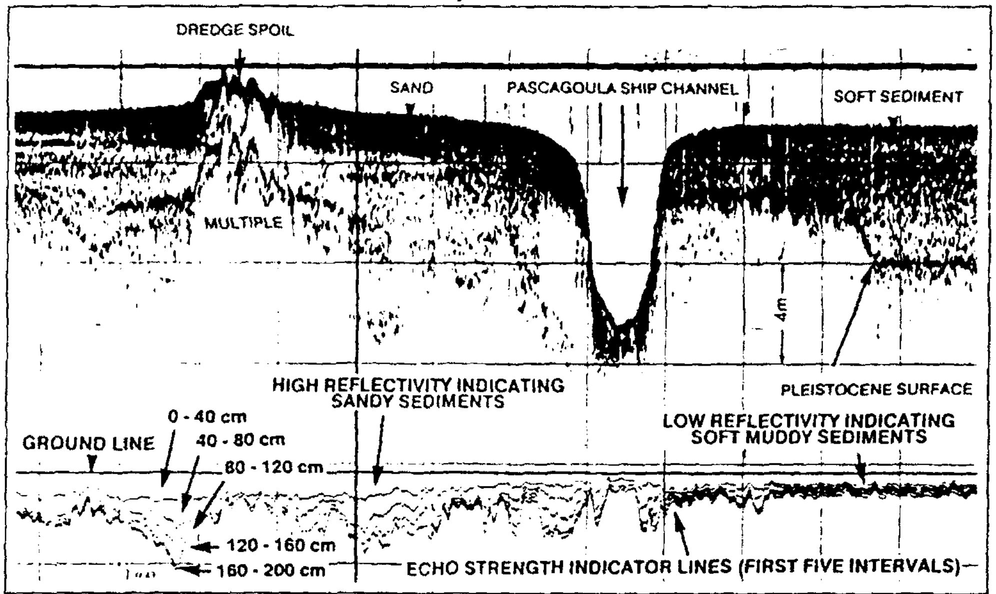


Figure 1. Typical ASCS 15 kHz analog seismic record with echo strength indicator line display.

The original ASCS was designed as a research tool with broad capabilities that allowed the updating of the software databases with improved sediment relationships as the users knowledge of the acoustic signal/seafloor interaction increased. The system was never intended to operate as a routine survey instrument nor did it have that capability. However, a strong need exists to have an easily operable, nearly automated remote seafloor classification system that can routinely produce seafloor properties maps for a multitude of applications. Therefore in mid-1990 NRL began a major project to significantly enhance the existing ASCS system. This began by developing a plan to upgrade the computer system to an 80486 microprocessor-based computer system running on the DOS operating environment, and verification and enhancement of the software, both in user friendliness and data processing and output capabilities. Since the DEC 350 and the 486 computers used incompatible operating systems, this required a complete rewrite of the ASCS software package. This effort was completed in early 1992, although it is expected that this software will continue to evolve and be further enhanced as the results of several other ongoing research efforts are integrated into the system. These efforts will be described under the Recent Developments and Current Developments sections below.

3. RECENT DEVELOPMENTS

The present ASCS is normally operated at 15 kHz and both quantitatively and qualitatively measures the amplitude (echo strength) and pulse character of the return acoustic signal in 10 adjustable-width time windows that correspond to depth increments in the sediment. The ASCS produces a high resolution analog seismic record of the upper few meters of the seafloor on which the amplitudes of the echo returns from the sediment depth increments are displayed. The dedicated 80486 computer is used to store and display the digitized raw echo strength and Global Positioning System (GPS) navigation in near real-time. The computer also provides the capability to apply algorithms based on multilayer acoustic theory to compute acoustic impedance for each of the depth increments in the sediment. This continuous profile of acoustic impedance is then used, in combination with a series of empirical relationships, to predict sediment structure and type, as well as various geotechnical properties such as attenuation, density, porosity, shear strength, compressional and shear velocity, and mean grain size. The new ASCS software is capable of displaying in near real-time each of these sediment properties either as a color scrolling waterfall-type display (Fig. 2) or as a scrolling tabular display of numerical values. Simultaneously displayed on the computer screen is a scrolling depth profile, a scrolling display of interpreted sediment structure, an oscilloscope-type display of echo strength, and a plot of the GPS navigation points along the tracklines which are color coded according to the corresponding impedance value of the upper sediment interval. The navigation plot then serves as a near real-time impedance map of the surficial sediments in the survey area.

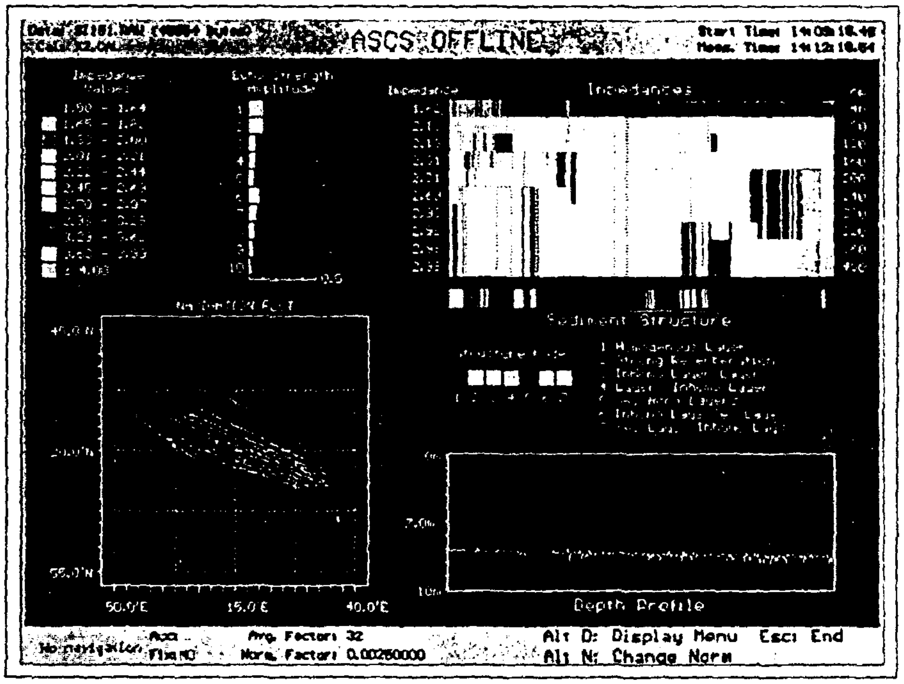


Figure 2. ASCS real time color display of sediment properties and GPS navigation.

Another recent development has provided the capability to collect co-registered side scan sonar data simultaneously with the ASCS data which allows a 3-D look at the upper several meters of the seafloor. This was accomplished for a survey run in the Mediterranean Sea in mid-1992. During this survey, an EDO 6991 broad band, full ocean depth rated transducer was mounted on a deep-tow sled along with an EG&G 990 side scan sonar operating at 59 kHz. The ASCS was operated at 15 kHz and its electronics integrated with the side scans telemetry system located in a pressure bottle on the sled. Data was telemetered to the ship through a 10,000 m coaxial tow cable. The electronics interface was designed so that each system could be operated independently, or simultaneously, and yet be completely transparent to the other so that there was no signal interference between the two instruments. In addition to producing the normal paper seismic record and the prediction of seafloor sediment properties through the ASCS software during this survey, a new data acquisition computer was added to the system which digitized and stored the outgoing acoustic pulse and the complete return signal at a resolution of 10 bits (resolution limit of the EG&G side scan telemetry system) and at a rate of 57 kHz. The data was stored on removable 90 Mbyte Bernoulli disk storage media. After approximately 3.5 hours of data collection, a full disk was removed and replaced by an empty one. Data from the full disk was then transferred on a third computer to inexpensive backup tape media for permanent storage and later processing. The digitization and storage of the complete acoustic signal for each ping provides for the ability to replay the raw data in the lab in order to make new analog records, to recalibrate the system during post processing, if necessary, to examine the acoustic signal on a ping by ping basis for research purposes, and to reprocess the data through the ASCS software after calibration to ground truth data. This combined survey system worked flawlessly throughout the cruise from the time the system was first deployed until the sled was badly damaged during a collision with the seafloor.

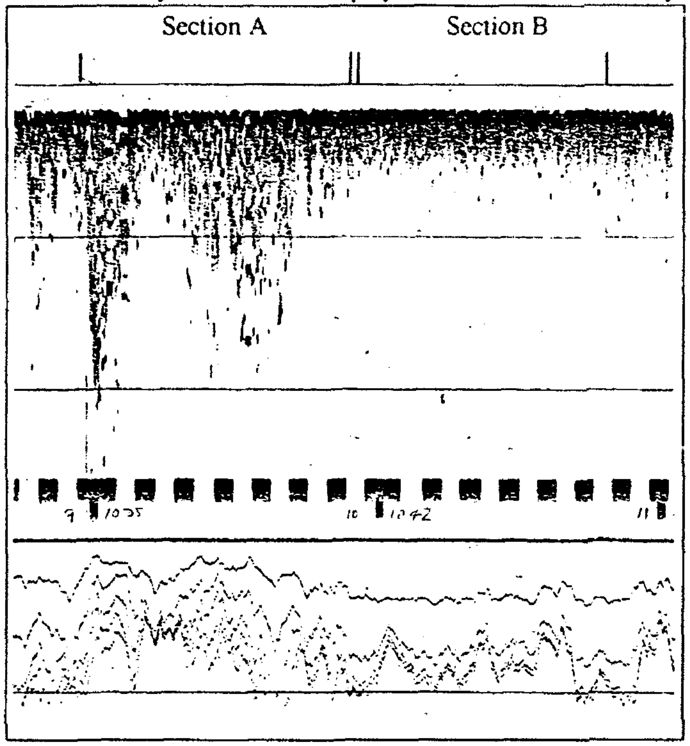
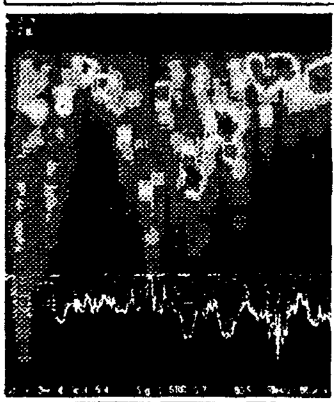
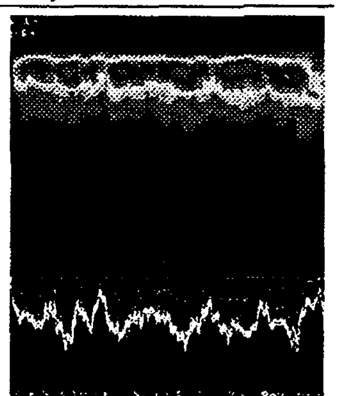


Figure 3. ASCS 15 kHz analog paper record across alternating low and high reflectivity sediments.

A new technique of displaying the digitized acoustic return as a function of amplitude vs. time (depth below the sediment/water interface) on a scrolling color monitor provides a dynamic range in excess of 60 dB and an extremely high resolution profile of the sediment structure. An analog paper record is limited to approximately 30 dB of dynamic range. For example, Figure 3 is an analog paper record collected in the Mediterranean Sea over a complex area of alternating deep penetration soft sediments (labeled Section A) and low penetration more reflective carbonate sediments (labeled Section B). Very limited internal structure within either sediment is visible in Figure 3. However, when the digital acoustic data is displayed on a color monitor (reproduced here in shades of gray) with intensity of the signal indicated in increments of 5 dB/color change, much more sediment structure is revealed. Sections A and B dramatically show this increase in sediment structure resolution, due to the increase of the dynamic range available for display. Another striking example is shown in Figures 4 and 5. Figure 4 is a typical ASCS 15 kHz analog paper record over a pipeline buried approximately 1.5 m in the seafloor. A trained observer can identify this object from the characteristic shadow below the pipeline and the echo strength display "fish mouth." In Figure 5 the data is displayed on a color monitor (B/W image shown here) with 5 dB steps of signal intensity indicated by color changes on the display. Note how well the pipeline stands out making such an object easily identifiable to the untrained eye.



Section A on Fig. 3



Section B on Fig. 3.

4. CURRENT DEVELOPMENTS

The ASCS system is currently undergoing a major development which is intended to meet the needs of several basic and applied research programs well into the future. From this effort, an optimized routine survey seafloor classification system will evolve. The heart of this development is an extremely robust system controller, data acquisition, data storage, and data processing hardware and software package. This system transmits an acoustic pulse, digitizes the acoustic return to 16 bits, records the raw data on a removable-media hard drive, and displays to the operator, in near real-time, three different displays:

(1) A scrolling waterfall-type color seismogram of the upper ten meters of sediment in which the color levels are adjustable in increments of the return signal intensity in dB.

(2) Ten echo strength intensity lines, which display the amplitude of the seismic return in each of ten intervals (adjustable widths presently of 10, 20, 40 or 80 cm) below the seafloor.

(3) An operator interface program which displays the current settings of the programmable system parameters, and allows the operator to change most of these parameters interactively with the observed data.

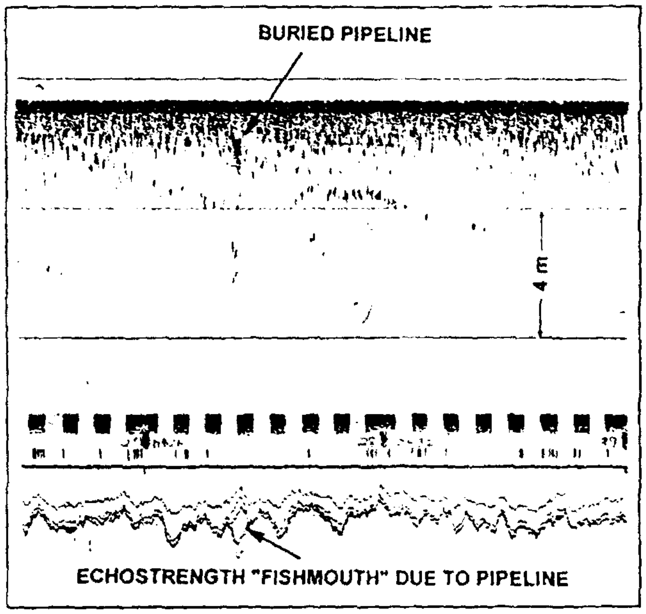


Figure 4. ASCS analog paper record across buried pipeline.

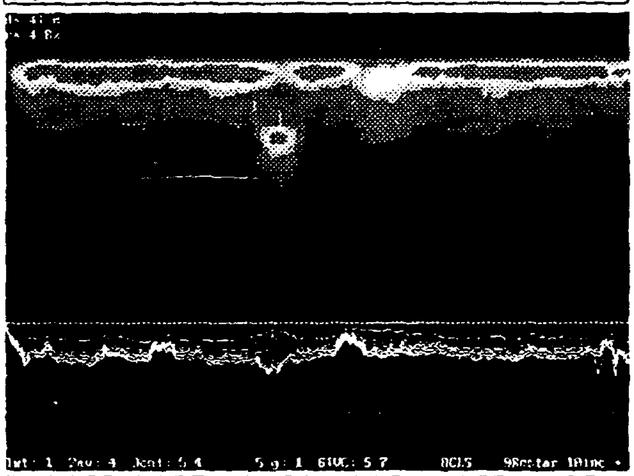


Figure 5. Color monitor display of digitized ASCS data across pipeline shown in Figure 6.

4.1. PROGRAMMABLE PARAMETERS

A key feature of the ASCS system under development is the programmability of most operational parameters including:

Function	Programmable Range
TRANSMITTER	
Frequency	1 - 100 kHz
Pulse Length	0.1 - 16 ms
Power Output	1 - 250 Watts
Repetition Rate	3 - 0.1 Hz (Pings/sec)
RECEIVER	
Gain	-20 dB to +63 dB
Amplitude Response	+/- 0.2 dB
Phase Response	+/- 0.002 Degree
DIGITIZER	
A/D Sample Rate	8 - 100 kHz
Resolution	16 bit[1]
Dynamic Range	96 dB
Anti-Alias Filter	>30th Order (FIR)[1]
REAL-TIME GRAPHICS	
Resolution	640 x 480 Pixels[1]
Type	Scrolling[1]
Colors	4 - 16
dB/color	4 - 8
Processing	2-D Averaging, Pixel Wtg
DATA RECORDER	
Type	Bernoulli 90 Hard Drive (90 MB)
Record Window	4,096 - 32,767 Bytes
Record Rate	320 kBytes/Second
File Type	DOS Binary File (2's Comp.)

Note: [1] - Non-Programmable Function

4.2. DATA ACQUISITION

The heart of the system is the 1 Mbyte of static random access memory (SRAM) shared by the both the 486 computer and the external data acquisition subsystem. This RAM operates as conventional computer RAM except in an acoustic data acquisition cycle, during which the SRAM is removed from computer address space and written into by the data acquisition unit. The maximum acquisition rate of the interface is therefore equal to the speed of the SRAM (currently 80 ns). Additional processing speed has been gained by dimensioning the SRAM address field as an integer array (encoded as 2's complement) within the acquisition program. The incoming raw data is immediately available to the 486 computer for processing without manipulation or conversion.

To begin the acquisition of a data set (one sounding) the system must first be armed by control software. After arming, the system will acquire a single data set. In order to avoid an accidental overwrite of valid data, the interface must be re-armed at the beginning of each sounding. After receiving the arm command the system must receive a "fire" command to initiate both the output transmission and collection of A/D converter samples. The FIRE command can originate from one of two sources: (1) from within the 486 computer - this is the stand-alone mode of operation, or (2) from an external source, in which data acquisition of the ASCS may be slaved to operation of a second system. In the external mode, the acoustic transmitter is disabled, in which case acoustic data is acquired passively.

The system interface and acoustic transmitter are installed on a circuit board located in an expansion slot of the 486 computer. A single external chassis, the Signal Conditioning Unit (SCU), houses the analog signal processing electronics, A/D converter, and power amplifier (PA). Control signals are passed in 8 bit parallel from the computer to the SCU. Digitized acoustic data is telemetered from the SCU into the computer as a synchronous serial data stream. The transmitter power amplifier, which can transmit a maximum of 250 watts, is powered from a linear 30 VDC power supply installed in the SCU.

4.3. TRANSDUCER
The ASCS transducer is an EDO model 6991, broad band from approximately 12 kHz to more than 30 kHz. This transducer can be hull mounted, or because of it's full ocean depth pressure compensation, can be mounted on a deep-tow sled, as was done during the Mediterranean survey. The transducer is used for both the transmit and receive functions and can be operated at a minimum of two acoustic frequencies: 15 and 30 kHz. At 15 kHz the beam width of the outgoing pulse is 12° and at 30 kHz it is 6°.

4.4. COMPUTER
The NRL ASCS system is based and presently controlled by two 33 MHz IBM-compatible 486 computers . One computer operates as the system controller, acquiring raw data, storing the raw data, and displaying the color seismogram in near real time. The second 486 computer is presently being used to run the ASCS software: to process the raw data in near real time, to compute an acoustic impedance profiles for each ping, and to predict sediment geotechnical properties along the trackline. In addition this computer stores the processed data for future replay and displays it on a color monitor as shown in Figure 2. As the new system is developed it is expected that all of these functions will be integrated into one software program operating on one 486 computer.

4.5. TRANSMITTER
The transmitter, operating Class S, outputs a phase coherent (pulse to pulse) square wave into the transducer power amplifier (PA). Designed into the system is the capability, if so desired in the future, of transmission of a source signature of practically any type (cw, pulsed cw, FM slide, or AM modulated). This source pulse can be programmed by the system operator, stored in RAM, and synchronously output in analog form via a digital/analog converter (DAC) residing in the computer.

4.6. RECEIVER
The receiver features programmable gain (-20 to +63 dB) and excellent amplitude/phase response at all gain levels of +/- 0.3 dB +/- 1.0 degree. The SCU gain change is possible, in 1 dB steps, during a seismic return, in order to achieve a digital, programmable TVG function, if required.

4.7. DIGITIZER
The system contains a monolithic 16-bit Sigma Delta A/D converter. The converter output sample rate is programmable from 8 to 100 kHz. The converter is capable of a second mode of operation, which outputs 12 bit data at a maximum sample rate of 400 kHz.

The SD was utilized primarily because of the performance advantages inherent in the digital anti-alias filter. The steep filter roll-off and linear phase response of the filter (>30th order at 0.45 Nyquist, 0.001 degree) virtually eliminates data artifacts attributable to under sampling (fold-back) and non-linear phase response (ringing) of a traditional analog anti-alias filter.

A third advantage of the Sigma-Delta converter is derived from the high over sample rate (128x) of the converter front end: even though the resolution of the converter is 61 mvolts, the output data is practically free from systematic noise (radiated/capacitively coupled high frequency clocks, power supply noise, etc) typically noticed in a 16-bit digitizer. The low noise level of the ASCS digitizer provides 92 dB of usable dynamic range, from the theoretical 96 dB available from a 16-bit converter.

In short, the A/D converter in combination with the magnitude and phase response of the system SCU will deliver data free of under sampling and SCU step-response artifacts. The net result is that the data output from the system contains a very accurate representation of the signal returned from the bottom.

4.8. DATA RECORDER

The ASCS raw data is recorded, as a DOS two's complement (integer) binary data file, to a Bernoulli 90 (90 Mbyte) hard drive. This drive has an 11 ms seek time. The system has attained hard drive transfer rates in excess of 320 kBytes/second. The Bernoulli recording media is removable: a cartridge can be changed in about 10 seconds, much like a floppy drive disk. For archiving large amounts (Gbytes) of data, we have, in the past, backed up the Bernoulli 90 cartridges to less expensive DCR tape cartridges.

4.9. REAL-TIME GRAPHICS

Real time graphics are provided to the system operator for purposes of data verification and to observe the effect of various programmable parameters (such as transmit frequency and pulse length) on the data quality. The seismic graphics are scrolling (left to right, as in most analog graphics recorders), and are designed to give the "feel" and appearance of a traditional seismic record. Screen resolution is 640 x 480 pixels. Sixteen colors, selectable from a palette of 256,000 colors, are available. Colors can be assigned from 4 - 8 dB/color. Currently, the graphics screen is configured for a vertical presentation of 12 meters of sediment.

Two processing algorithms are currently used in the real-time seismic data presentation. the first, a data smoothing algorithm, averages a user selectable number of vertical samples of the input (raw) data. The effect of this operation is a 1 dimensional low-pass filter. The smoothed data is input into the second display algorithm, a simple 2-dimensional average of each pixel with each of the eight surrounding pixels. The relative importance of the central pixel, or weight, is a user programmable input. The net effect of these processing algorithms is to present the data, in near real-time, to the operator in such as manner that the data quality, or utility, can be determined. The particular real-time graphics parameters selected by the operator do not effect data stored onto hard disk, which always stores the raw A/D data. These processing algorithms operate in the data playback mode, in which previously recorded data is played back (from disk) into the system.

A second data recording system, which will record the real-time data acquisition graphics screen onto a VCR recorder, is currently under investigation. This technique will allow a data processor to review large amounts of previously recorded data very quickly.

The second real-time graphics presented to the system operator is the intensity line display, located toward the bottom of the seismic graphics. These ten lines display the relative intensities of the seismic return in ten programmable intervals into the sea floor. The intensity lines are characteristic of seafloor type, i.e., soft sediments, sands, etc., and can be quickly scanned.

The operator interface is displayed at the very bottom of the real-time acquisition screen. This is a scrolling menu from which programmable system parameters may be verified or changed. Any change to a system parameter is updated and becomes effective at the beginning of the next seismic shot.

5. FUTURE DEVELOPMENTS

As of this writing, several basic and applied research projects are ongoing which will strongly influence the future developments and evolution of the ASCS as a routine survey instrument. One such basic research project is investigating the fundamental physics of acoustic interaction with the seafloor. This theoretical study and modeling effort will use the results of an evaluation of the current ASCS sediment classification algorithms to explore a number of signal processing techniques that can provide the quantification of seafloor micromorphology required for improved sediment classification. Techniques that are being investigated include the simultaneous use of two or more frequencies, parallel processing, artificial intelligence, and the use of the total acoustic signal for sediment classification. Concurrent investigations are being conducted to determine the feasibility of supplementing or replacing the present empirical relationships used in sediment properties prediction with suitable physical models, Richardson and Briggs (6).

A recent field experiment in the Baltic Sea has shown that when an extremely stable transducer platform is used that a 30 kHz acoustic pulse with a 6° beam width produces a seismic record nearly equivalent in penetration depth to that of a pulse at 15 kHz with a 12° beam width, but with higher resolution of sediment structure. We also experimented with various pulse lengths and power levels of the acoustic signal and found that reducing the pulse length from 0.35 ms to 0.1 ms while increasing the input power level from 100 w to approximately 250 w further increases resolution without serious loss of penetration. One goal of this effort is to be able to decrease the sediment classification window size to 10 cm or less while increasing the number of measuring windows to 50 for detailed sediment classification to a depth of five meters.

NRL is presently designing a stable tow body on which the ASCS transducer will be mounted along with the transducers from a high resolution side scan sonar. This will provide the capability to deep tow the combined systems to a depth of 1,500 m and collect co-registered side scan and ASCS data for a 3-D survey of the seafloor. This system will be portable and self-contained with its own winch and cable for easy deployment off nearly any vessel.

Another project is developing automated methods of handling the large amounts of data collected by the ASCS over a survey area. Commercially available gridding and contouring software and geographical information system (GIS) software is being integrated with the ASCS software in order to provide the capability to automatically output detailed 3-D sediment properties maps over the area surveyed. This effort will greatly reduce the amount of post-processing time required to interpret the results of a survey, and hopefully allow the generation of preliminary maps while still in the field.

6. ACKNOWLEDGMENTS

Several programs have provided funding support for the ASCS research effort. The Coastal Benthic Boundary Layer Special Research Program, Program Element 61153N, Dr. Michael Richardson, Chief Scientist, is providing funding for the 6.1 basic research work. The MTEDS Program, Program Element 62759N, Mr. Sam Tooma, Program Manager, is providing funds for research in the 6.2 Exploratory Development area. The ASW Environmental Acoustics Support Program, Program Element 63785N, Mr. Barry Blumenthal, Program Manager, has provided funding for the Mediterranean Sea survey work and for the automated database development project. Funding for the ASCS software development has been provided through the Naval Oceanographic Office, Mr. Larry Reynolds, project Technical Monitor. NRL's Capital Purchase Program is providing funding for the integrated ASCS/side scan sonar deep-tow survey system development.

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